



Community Plan for Far-Infrared/Submillimeter Space Astronomy

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This paper represents the consensus view of the 124 participants in the “Second Workshop on New Concepts for Far-Infrared/Submillimeter Space Astronomy,” which was held on 7 – 8 March 2002 in College Park, Maryland. The participants are listed below.

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Community Plan for Far-Infrared/Submillimeter Space Astronomy

We recommend that NASA pursue the vision for far-IR astronomy outlined in the NAS Decadal Survey, which said: “A rational coordinated program for space optical and infrared astronomy would build on the experience gained with NGST¹ to construct [a JWST-scale filled-aperture far-IR telescope] SAFIR, and then ultimately, in the decade 2010 to 2020, build on the SAFIR, TPF, and SIM experience to assemble a space-based, far-infrared interferometer.” SAFIR will study star formation in the young universe, the buildup of elements heavier than hydrogen over cosmic history, the process of galaxy formation, and the early phases of star formation, which occur behind a veil of dust that precludes detection at mid IR and shorter wavelengths. The far-infrared interferometer will resolve distant galaxies to study protogalaxy interactions and mergers and the processes that led to enhanced star formation activity and the formation of Active Galactic Nuclei, and will resolve protostars and debris disks in our Galaxy to study how stars and planetary systems form.

The following unified plan addresses practical issues and makes recommendations that would lead to the fulfillment of the Decadal Report’s vision. This plan gives the consensus view of the participants in the “Second Workshop on New Concepts for Far-Infrared/Submillimeter Space Astronomy,” which was co-sponsored by NASA Headquarters and the Goddard Space Flight Center and held at the University of Maryland on 7 – 8 March, 2002. The workshop participants were representatives of the community of scientists and technologists who would implement the plan.

We make these recommendations to NASA because information vital to the attainment of major SEU and Origins scientific objectives is uniquely available in the far-IR and submillimeter (FIR/SMM), a spectral range that spans the gap between the longest wavelength accessible to the JWST (formerly NGST), ~25 μm , and the shortest wavelength continuously accessible to ALMA through the atmosphere, ~800 μm . For example, to “understand the structure of the universe, from its earliest beginnings to its ultimate fate,” we will need measurements of the emissions from protogalactic objects and galaxies most intimately related to the star formation process, namely emissions that reveal the physical conditions (elemental abundances, temperatures, densities) in the interstellar medium; we will need extinction-free views of the universe complementary to those provided by telescopes that operate at shorter wavelengths; and we will need telescopes that can measure the emissions from the pristine hydrogen clouds that collapsed to form the very first generation of stars. To “explore the ultimate limits of gravity and energy in the universe” we will need to peer into the dust-enshrouded nuclei of galaxies to see how matter behaves in the presence of a supermassive black hole. To “learn how stars and planets form” we will need to observe these objects where they emit most of their light – in the infrared – with telescopes that provide high enough spectral resolution to constrain theoretical models, and sufficient acuity to resolve extrasolar planetary systems. Some of the objects we wish to study – the youngest stars and galaxies – are not even visible at optical and near-IR wavelengths.

¹ See Appendix A for acronym definitions.

The value of infrared spectroscopy is evident in the information-rich data from NASA's Submillimeter Wave Astronomy Satellite (SWAS) and ESA's Infrared Space Observatory (ISO). Spectroscopic data give us information on chemical species, velocities, and the interaction of these in the chemodynamics that is virtually certain to play a dominant role in the next stage of astrophysical thought. High spectral resolution will therefore be an essential capability for future FIR/SMM missions.

The FIR/SMM is the least-explored spectral region in astronomy, even though COBE told us that half the luminosity of the universe, and 98% of the photons (aside from the cosmic microwave background), appear in the far-IR. Far-IR astronomy has been hampered by angular resolution worse than that of Galileo's first telescope, and by sensitivity limited by small apertures and early generations of detectors. Even SIRTf is still modest in size, only a little larger than the IRAS flown in 1982. The Herschel telescope at 70 K and the SOFIA telescope at 250 K will be about 4x and 3x larger, respectively, but are both relatively warm for this wavelength regime, and thus have limited sensitivity. The scientific yield of the upcoming missions SIRTf, SOFIA, and Herschel will whet our appetites for more sensitive FIR/SMM telescopes that can be used to detect the faint emissions from young, and therefore distant, galaxies. A further gain in sensitivity by several orders of magnitude is necessary to see these sources, and is attainable with a large aperture space observatory whose sensitivity is limited only by the insurmountable photon noise from astrophysical background radiation. New technology and mission concepts now enable a major breakthrough in this area, with the confident expectation of new discoveries.

First Step: SAFIR

The first step is to develop the technology and start the planning for a cooled JWST-class far-IR observatory called SAFIR (Single Aperture Far-IR telescope), to be operated like HST for a wide user community with a launch by the middle of the JWST lifetime in 2015. The scientific motivation and concepts for SAFIR are presented in the white paper *Charting the Winds that Change the Universe* (Appendix B). SAFIR should be background limited over a wavelength range from about 15 to 600 μm to overlap slightly with JWST and ground-based capabilities, and could be diffraction limited at around 40 μm . With a 10 m aperture (a little larger than JWST's) it would have 150 times the collecting area and an order of magnitude greater angular resolution at a given wavelength than SIRTf. Figure 1 shows the relevance of this improvement in angular resolution to the measurements needed to achieve Origins and SEU science objectives, and the striking gap in resolving power in the FIR/SMM that will be left in the wake of the next generation of telescopes. SAFIR will provide our first deep view of the sky at far-IR wavelengths that does not suffer the ill effects of extragalactic source confusion (multiple galaxies per resolution element), enabling detailed studies of the individual sources that give rise to the cosmic IR background.

SAFIR instruments would provide imaging and spectroscopic capabilities with maximum spectral resolution $\lambda/\Delta\lambda \sim 10^6$. To achieve the goal of natural background-limited performance, the SAFIR mirror will have to be cooled to about 4 K, and new generations of detectors, operating at about 0.05 K, will have to have NEP $< 10^{-20}$ W Hz^{-1/2}. With such

extraordinary sensitivity SAFIR could readily detect spectral line emission and spectral features from gas and dust in galaxies at redshift $z \sim 4 - 5$, as illustrated in Figure 2, and probe the gas dynamics and chemistry in forming planetary systems. Figure 2 further shows the importance of improving sensitivity by 4 - 5 orders of magnitude beyond the capabilities of SIRTf, SOFIA, and Herschel. Japan's SPICA mission, which is planned to have a 4 K, 3.5 m diameter primary mirror, will take a huge step in this direction. SAFIR, with its larger mirror, will bring the most distant galaxies into range.

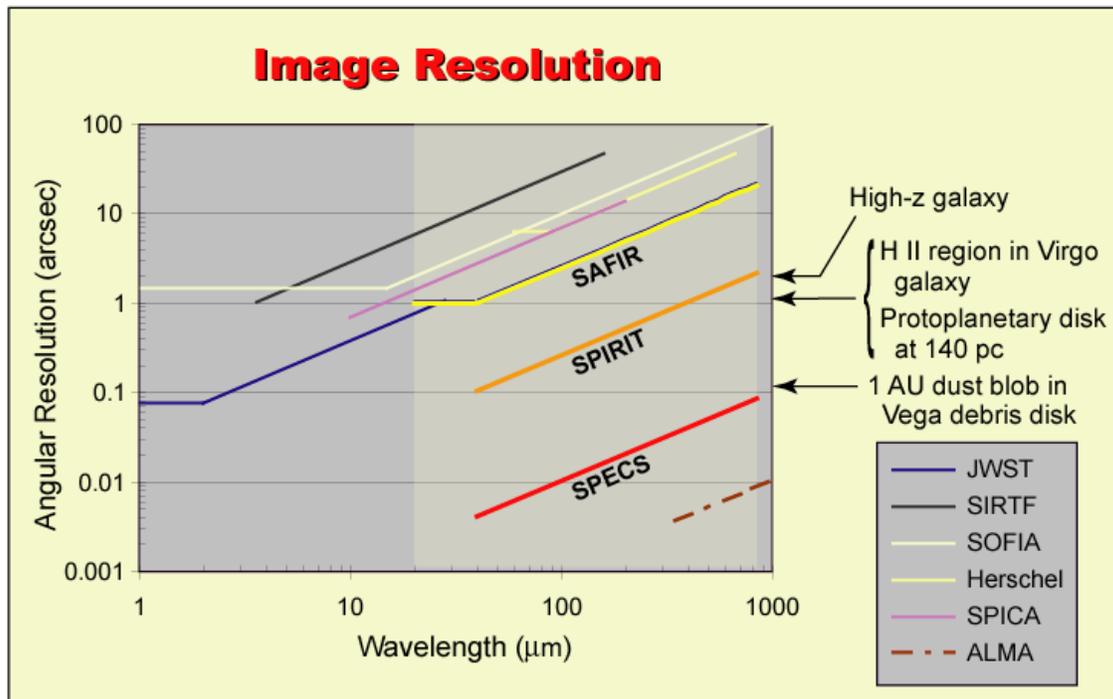


Figure 1. Vast improvements in angular resolution beyond those provided by the next-generation FIR/SMM missions will be needed to beat extragalactic source confusion, resolve the individual sources of interest, and achieve the science goals of NASA's Origins and SEU themes. Such improvements are also needed to align the FIR/SMM (shaded region) measurement capability with that available in the surrounding spectral regions, where JWST and ALMA will make complementary observations. ALMA provides complete spectral coverage at wavelengths longer than $\sim 800 \mu\text{m}$ and observing capability into the submillimeter through atmospheric windows. With a 10 m aperture diameter SAFIR will take the first big step; interferometers like SPIRIT (assumed maximum baseline $b_{\text{max}} = 40 \text{ m}$) and SPECS ($b_{\text{max}} = 1 \text{ km}$) will be needed to provide the full resolution gain desired. SAFIR, SPIRIT, and SPECS are recommended in this plan.

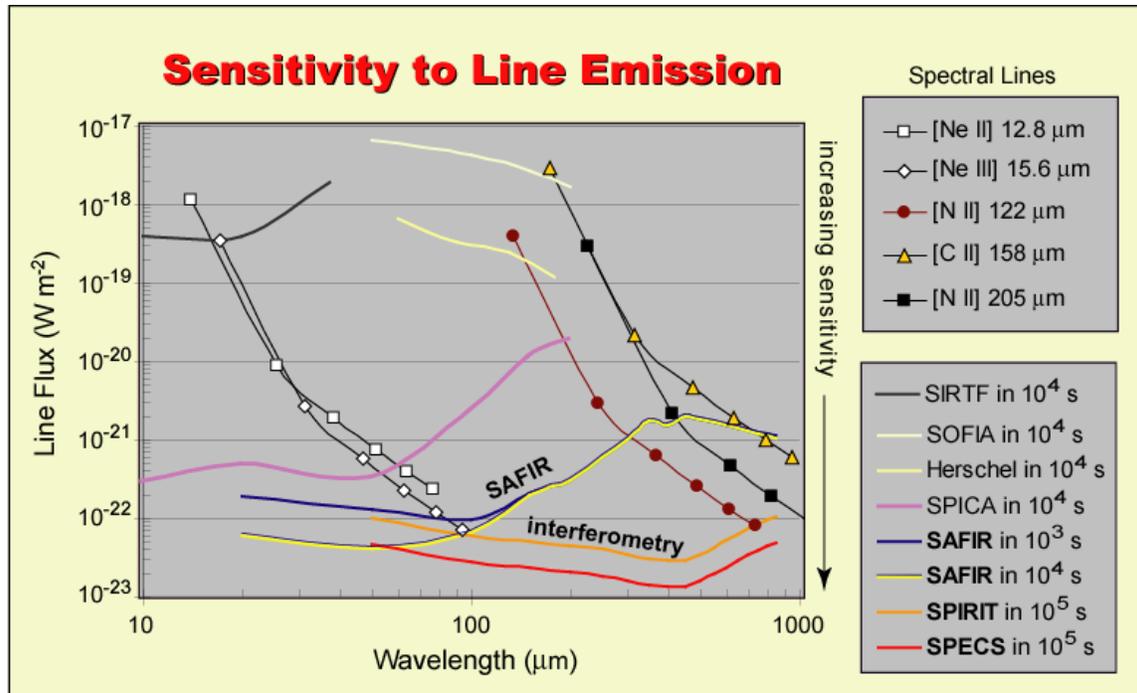


Figure 2. A spectrometer on SAFIR (with assumed $\lambda/\Delta\lambda = 10^3$) would be 4 to 5 orders of magnitude more sensitive than the corresponding instruments on SIRTIF, SOFIA, and Herschel, and 1 to 2 orders of magnitude more sensitive than SPICA, enabling unprecedented studies of the star formation process and astrophysical conditions in distant, young galaxies. Estimated strengths of five important diagnostic and interstellar gas cooling lines are shown for a hypothetical “Milky Way” galaxy at redshifts of 0.1, 1, 2, 3, 4, and 5 (symbols along each curve, with redshift increasing from the upper left to the lower right). The rest wavelengths of the spectral lines are given in the inset. SAFIR could, for example, measure the [Ne II] and [Ne III] lines in “normal” galaxies out to $z = 5$ in modest exposure times. The relative intensity of these lines can be used to discriminate between AGN-dominated and star formation-dominated emission. Many galaxies are much more luminous than the Milky Way, making them even easier to see. At $\lambda > 200 \mu\text{m}$, SAFIR would reach the confusion noise “floor” in about 100 seconds²; longer exposure times would not help. However, because of their greater resolving power and still substantial total aperture areas, the interferometers SPIRIT and SPECS will break the confusion barrier and probe the universe to comparable depth (redshift $z \sim 5$) in the spectral lines that dominate the cooling of interstellar gas and allow the gas clouds to collapse and produce stars.

SAFIR will require investment in several technology areas. High-sensitivity far-IR detector technology, which is very promising but far from flight readiness, is one of the top priority items for SAFIR preparations. A total investment of the order of \$50 M spread out over 10 years could produce large superconducting detector arrays with sensitivity one or two orders of magnitude beyond those now available, satisfying the performance goal. Even this budget is small compared with the investments made in

² We assume that the emission found in a single diffraction-limited beam cannot be reliably apportioned between multiple component sources. Therefore, we show the continuum confusion limit in a single $\lambda/1000$ spectral channel. The sensitivity would be less severely compromised by confusion if the redshift of each component were known from independent observations.

detectors at other wavelengths, but NASA is the only effective funding source in this area. Depending on the results and scientific opportunities developed from the Herschel mission, SAFIR might require coherent receivers that approach quantum-limited performance, as well as direct detectors.

Sensitivity in the FIR/SMM depends strongly on the temperature of the telescope, and it is imperative that improvements in detector technology be matched by efforts to cool large mirrors to very low temperatures. Because the optical tolerances on the SAFIR mirror are greatly relaxed relative to the JWST requirements, the possible use of precision machined, replicated mirror segments should be explored. Replication has the potential to speed fabrication and reduce cost. Based on JWST experience, we conclude that such a mirror study would cost \$25M over three years, and the mirror technology could reach maturity (TRL 6) in a total of six years. The Advanced Cryocooler Technology Demonstration will provide a small TRL 5 cooler in 2005, but a much more powerful cooler will be needed to cool the SAFIR mirror. A development program for new cryocooler systems would cost about \$30 M. Other projects, like JWST and TPF, and other government agencies (DoD and NRO) are already providing technology development funds for advanced coolers and deployable mirrors.

Whereas a JWST-like configuration flying at 3 – 4 AU from the Sun was shown in the Decadal Survey report, better thermal and sunshield engineering will permit SAFIR to operate at the JWST L_2 orbit and provide a larger aperture with the same launch vehicle. Other configurations should also be explored (Fig. 3).

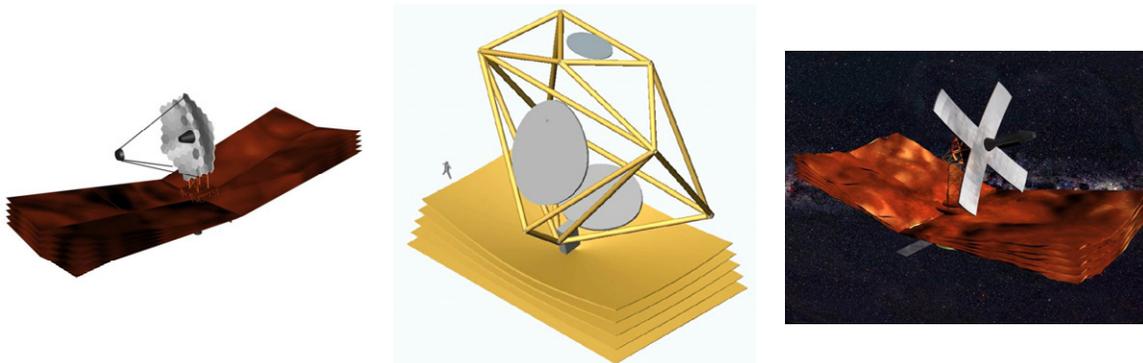


Figure 3. Further study of SAFIR mission designs will be needed before a single approach that accomplishes the highest priority science goals with ready technology, subject to programmatic considerations, can be selected. Three possible concepts are shown here: (left) based on JWST for maximum heritage and fidelity; (middle) based on stretched membrane mirrors to reduce aerial mass; and (right) based on a sparse aperture telescope to improve angular resolution.

Depending on the progress made with other planned instruments, a FIR/SMM all-sky survey mission with a 2 m class cryogenic telescope might be a scientifically compelling precursor to SAFIR. At other wavelengths, survey missions have greatly enhanced the science return of successive observatories. In the far-IR, the last sky survey, IRAS, was so insensitive that SAFIR will be blinded by every IRAS source. Given the immense discovery potential in this relatively unexplored spectral region, it is reasonable

to think that a deep FIR/SMM survey will be needed, and to plan accordingly. It is presently believed that there are many submillimeter-luminous galaxies at very high redshifts that do not have noteworthy optical counterparts, but which make up a substantial fraction of the total luminosity of the post-recombination universe. If these sources are not identified by SIRTf, Astro-F, NGSS, SOFIA, Herschel, or SPICA - because of their limited sensitivity, shorter wavelength range, or smaller survey area - then a FIR/SMM survey should be undertaken, and we believe that such a mission would be a strong competitor in the Discovery class. A sensitive FIR/SMM sky survey would answer important questions about the evolution of galaxies and would find the rare but important objects that act as signposts to the early universe, providing a rich database to build on with SAFIR and other missions.

Second Step: SPECS

The imaging sensitivity of SAFIR will be limited by the overlap of distant galaxy images at wavelengths greater than about 100 μm because its angular resolution will be ~ 3 arcsec, comparable to that of binoculars and to the spacing of galaxies seen in the Hubble Deep Field. A very large increase in angular resolution would be possible with an interferometer (Fig. 1). The scientific motivation and concepts for two FIR/SMM interferometry missions are presented in the white paper *Probing the Invisible Universe* (Appendix C). **A commendable long-range goal is to achieve HST-class resolution in the FIR/SMM, which would require an imaging interferometer with a 1 km maximum baseline.** Although this is not currently technically feasible, it is less challenging than X-ray or optical interferometry in space because the FIR/SMM wavelengths are much longer, and is comparable in overall difficulty to the other interferometry missions deemed meritorious by the astronomical community and included in the NASA Roadmap. We outline below the technical steps that will be required to build the km-baseline interferometer we call the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS).

A FIR/SMM interferometer with superconducting detectors, cold mirrors, and a total light collecting aperture in the tens of m^2 would provide ample sensitivity. To derive the sensitivity curve shown for SPECS in Figure 2, the interferometer was assumed to combine the light collected with three 4 m diameter mirrors. SPECS is a natural successor to SAFIR, as it would employ the same detector, mirror, and cooler technologies, although the interferometer mirrors would be smaller than the SAFIR mirror and could be monolithic.

Three additional technologies or techniques will be needed to enable long-baseline imaging interferometry: a long-stroke cryogenic delay line; highly-reconfigurable formation flying; and the technique of wide-field imaging interferometry. Initial funding for these technologies was awarded through competitive programs during the past several years, and continued support for these mission-enabling technologies is needed. High-risk technologies, such as tethered formation flying, should be demonstrated in space with inexpensive nanosats.

Following a recommendation made by the attendees of the first community workshop in this series, “Submillimeter Space Astronomy in the Next Millennium,” which took place in February 1999, concepts were developed for a FIR/SMM interferometer on a boom. We call this the Space Infrared Interferometric Telescope (SPIRIT). Figures 1 and 2 show that such a telescope would have very powerful measurement capabilities. A suitable goal for SPIRIT would be a system with a 40 m span, which provides the same angular resolution as a filled aperture telescope nearly twice this diameter and matches the JWST’s resolution, but at a wavelength 10 times longer (see Fig. 1). Such a structure is within reach of the expected technology base 5 to 10 years from now, as much larger booms are already in use in space. Good metrology and active control are required, but diffraction limited performance at 40 μm is quite easy to achieve relative to the performance required for an optical interferometer, and SIM is paving this path. The apertures should be as large and as cold as can be afforded, but for this step it is clear that angular resolution is more important than sensitivity. To estimate the sensitivity shown in Figure 2 we assume that SPIRIT has two 3 m diameter light collecting mirrors, and the mirror temperature is 4 K. **If the cost of SPIRIT is much less than that of a “roadmap mission” like SPECS, as preliminary studies indicate, then SPIRIT should precede SPECS. We recommend that FIR/SMM interferometry mission concept studies be continued.**

As illustrated in Figure 4, the new technology requirements for FIR/SMM interferometry largely overlap the requirements for SAFIR.

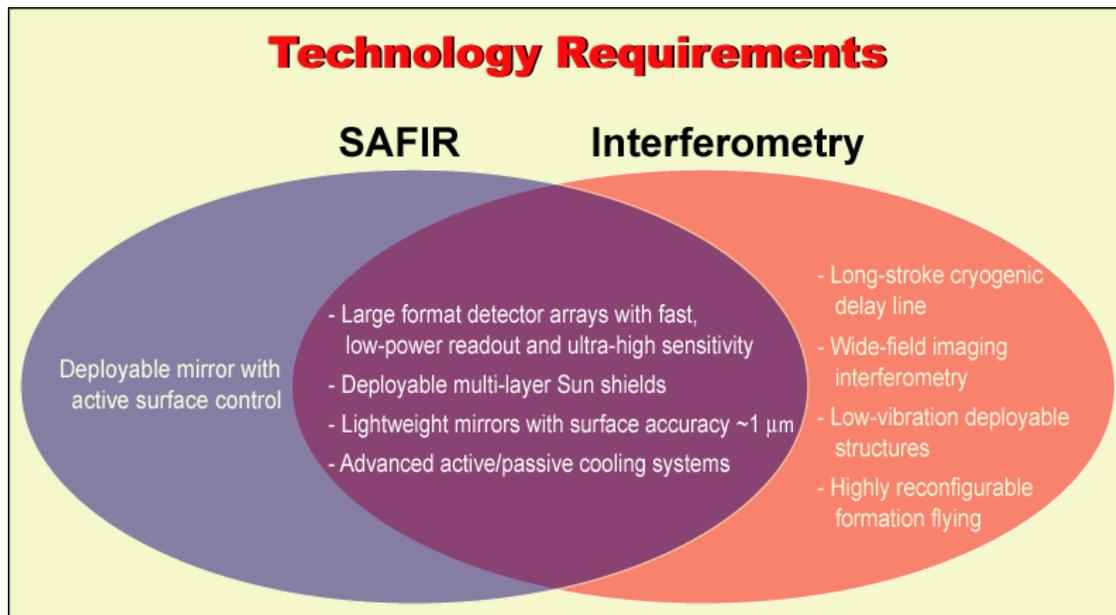


Figure 4. Investments in SAFIR technology will go a long way toward enabling FIR/SMM interferometry, and some of the interferometry technologies will be needed for LISA, SIM, and possibly TPF. New detectors and large mirror cooling technologies are particularly critical for FIR/SMM space astronomy, but a coordinated technology program would invest early in all the long lead time technologies shown here.

Supporting Research, Technology, and Missions

Several years will pass before it becomes necessary to choose design details for SAFIR and SPECS, and some decisions, such as the option to fly a far-IR sky survey mission, and the relative timing of the SPIRIT and SAFIR missions, will depend on future scientific progress, on experience with JWST, ALMA, and ground-based optical interferometers, on the available technology, and on budgetary constraints. However, a relatively modest investment is needed to prepare. **We recommend a coordinated technology program** that provides support for the development of:

1. 10^4 pixel arrays of direct detectors with NEP $\sim 10^{-20}$ W Hz^{-1/2},
2. advanced, high-efficiency cryocoolers capable of providing ~ 100 mW of cooling power at 4 K for mirror cooling, and capable of cooling the detectors to ~ 50 mK,
3. low-cost, low areal density (< 15 kg/m²) mirror technology for the FIR/SMM in a mirror development program that includes
 - a) demonstration of fabrication techniques,
 - b) demonstration of cooling strategies,
 - c) demonstration of wavefront sensing and control, and
 - d) development of test procedures,
4. interferometry testbeds that can be used to develop procedures, algorithms, and control systems,
5. broadband tunable coherent THz array receivers that approach quantum-limited performance,
6. long-stroke cryogenic delay lines and compact spectrometer technology for broadband FIR/SMM spectroscopy and wide-field imaging using direct detectors,
7. low-vibration deployable structures, and
8. highly-reconfigurable formation flying to enable interferometric (u, v) plane filling, and therefore high contrast imaging.

Successful development of the technologies listed above would serve many NASA purposes. All of the FIR/SMM missions demand new detector development, and there is a strong overlap of technology with some types of X-ray and UV detectors. For example, Con-X needs superconducting detectors and cryo-coolers. LISA, like SPECS, requires formation flying. Some of the interferometry technologies are shared with other planned NASA missions, such as SIM and the interferometer version of TPF, although SIM and TPF require much better precision to work at shorter wavelengths and make astrometric measurements or null out starlight.

We recommend that NASA support initial concept studies for SAFIR, SPIRIT, SPECS, and a sensitive FIR/SMM all-sky survey mission. SPIRIT and the sky survey mission would cost less than SAFIR or SPECS, but more than the current MIDEX cap, and would therefore require either \$400M-class Space Science mission opportunities or collaboration with partners to bring down the NASA cost. NASA has been asked to collaborate on the planned Japanese SPICA mission, which would provide a 3.5 m class cold far-IR telescope at the Lagrange point L₂. NASA would benefit from the opportunity to deploy new generations of far-IR detectors and instruments in space. New detector technology can be tested and used first on SOFIA, but SPICA may be the nearest term opportunity to use next-generation far-IR detectors in space.

Finally, **we recommend that NASA be receptive to proposals for laboratory and theoretical astrophysics related to far-IR studies.** Relatively little is known about the chemical reactions that form large interstellar molecules or dust, or their role in the physical processes that govern star and planet formation. As new species and phenomena are recognized from observations, it will be very important to interpret them accurately. It is also clear that simulations are critically important in establishing the right observing strategies and instrument requirements.

European and Japanese astronomers are eager to collaborate with their US colleagues on SAFIR and FIR/SMM interferometry. The European community will desire opportunities to follow up the Herschel mission, and the Japanese community to follow up the SPICA mission.

Conclusion

Information needed to answer some of the most compelling astrophysical questions is uniquely available in the FIR/SMM spectral region. The time is right to place SAFIR on the NASA plan as one of the successors of SIRTf and JWST, to set our sights on a long-baseline FIR/SMM interferometric imaging telescope, to further develop FIR/SMM single-aperture and interferometric mission concepts, and to invest strategically in the technology that will enable future FIR/SMM missions. Supporting studies and smaller mission opportunities should be actively pursued.

Appendix A. Acronyms

AGN – active galactic nucleus
 ALMA – Atacama Large Millimeter Array
 Astro-F – Japanese Infrared Imaging Surveyor
 Con-X – Constellation X
 ESA – European Space Agency
 FIR/SMM – the far-infrared and submillimeter wavelength range from ~25 – 800 μm
 IRAS – Infrared Astronomical Satellite
 ISO – Infrared Space Observatory
 JWST – James Webb Space Telescope, formerly NGST
 LISA – Laser Interferometer Space Antenna
 MIDEX – NASA’s Medium-class Explorer program
 NEP – Noise Equivalent Power
 NGSS – Next Generation Sky Survey, a MIDEX mission
 NGST – Next Generation Space Telescope, now called JWST
 SAFIR – Single Aperture Far-Infrared Telescope
 SEU – NASA’s Structure and Evolution of the Universe theme
 SIM – Space Interferometry Mission
 SIRTF – Space Infrared Telescope Facility
 SOFIA – Stratospheric Observatory for Infrared Astronomy
 SPECS – Submillimeter Probe of the Evolution of Cosmic Structure
 SPICA – Space Infrared Telescope for Cosmology and Astrophysics, formerly HII/L2
 SPIRIT – Space Infrared Interferometric Telescope
 SWAS – Submillimeter Wave Astronomy Satellite
 TPF – Terrestrial Planet Finder
 TRL – technology readiness level

Appendix B. *Charting the Winds that Change the Universe, II. The Single Aperture Far Infrared Observatory (SAFIR)*

This document can be found on pages 157-166 of these proceedings.

Appendix C. *Probing the Invisible Universe: The Case for Far-IR/Submillimeter Interferometry*

This document can be found on pages 167-177 of these proceedings.